An Intensive Observation of Calving at Helheim Glacier, East Greenland

David M. Holland[1,2*]
Denis Voytenko[1]
Knut Christianson[3]
Timothy H. Dixon[4]
M. Jeffrey Mei[5,6]
Byron R. Parizek[7]
Irena Vaňková[1,2]
Ryan T. Walker[8]
Jacob I. Walter[9]
Keith Nicholls[10]
Denise Holland[1,2]

[1]Courant Institute of Mathematical Sciences, New York University, New York, NY, USA
[2]Center for Global Sea Level Change, NYU Abu Dhabi, Abu Dhabi, UAE
[3]Department of Earth & Space Sciences, University of Washington, Seattle, WA, USA
[4]School of Geosciences, University of South Florida, Tampa, FL, USA
[5]Department of Applied Ocean Science & Engineering, Woods Hole Oceanographic Institute, Woods Hole, MA, USA
[6]Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[7]Mathematics & Geoscience, The Pennsylvania State University, DuBois, PA, USA
[8]Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA
[9]Institute for Geophysics, University of Texas at Austin, Austin, TX, USA
[10]British Antarctic Survey, Cambridge, UK

*Correspondence to: david.holland@nyu.edu

ABSTRACT

Calving of glacial ice into the ocean from the Greenland Ice Sheet is an important component of global sea-level rise. The calving process itself is relatively poorly observed, understood, and modeled; as such, it represents a bottleneck in improving future global sea-level estimates in climate models. We organized a pilot project to observe the calving process at Helheim Glacier in east Greenland in an effort to better understand it. During an intensive one-week survey, we deployed a suite of instrumentation, including a terrestrial radar interferometer, global positioning system (GPS) receivers, seismometers, tsunameters, and an automated weather station. We were fortunate to capture a calving process and to measure various glaciological, oceanographic, and atmospheric parameters before, during, and after the event. One outcome of our observations is evidence that the calving process actually consists of a number of discrete events, spread out over time, in this instance over at least two days. This time span has implications for models of the process. Realistic projections of future global sea level will depend on an accurate parametrization of calving, and we argue that more sustained observations will be required to reach this objective.

1 INTRODUCTION

Over the past few years major changes have been observed along the periphery of the Greenland Ice Sheet, occurring much faster than previously thought possible [Joughin et al., 2004, 2008]. Glacier frontal position and velocity data, largely measured by satellite remote-sensing, indicate that outlet glaciers in both east and west Greenland have retreated, thinned, and accelerated quasi-synchronously [Luckman et al., 2006; Rignot & Kanagaratnam, 2006; Moon & Joughin, 2008]. These correlated responses suggest that a common thermodynamic forcing is at play. Whether an increase in air temperature [Moon & Joughin, 2008], ocean temperature [Holland et al., 2008], or some combination is responsible, the mechanisms linking the forcing to subsequent dynamical retreat of the calving front, inland thinning, and acceleration remains to be resolved.

While questions about thermodynamic forcing have received significant attention, present understanding of the mechanisms controlling ice-sheet dynamics is itself limited. As a consequence, projecting the magnitude of sea-level rise associated with possible retreat of the Greenland Ice Sheet remains challenging. The latest IPCC Assessment Reports [2007, 2013] acknowledge that key glacier processes are not well understood, limiting ability to accurately project sea-level rise [Joughin et al., 2012]. Grounding line dynamics [Schoof, 2007], basal drag [Vaughan & Arthern, 2007], and iceberg calving [Benn et al., 2007] are among the crucial processes that now require intensive investigation. Currently, limited knowledge of these processes is an inherent reflection of their complexity, and the difficulty of making field measurements, which can be both costly and hazardous. Calving of icebergs is an important component of the negative mass budget of the Greenland Ice Sheet [Benn et al., 2007]. It can be argued that calving is the least understood of these processes, while at the same time probably the most critical to understanding ice sheet retreat [DeConto & Pollard, 2016].

We focused on the calving process for a typical Greenland outlet glacier, in particular one now in retreat and without a floating ice tongue, a so-called tidewater glacier. A characteristic of the calving process there, as we will demonstrate, is that it occurs over a period of at least a few days, consisting of a sequence of events during which mechanical failure of the glacier occurs. There can be precursor events during which fracture occurs in the glacier, days, hours, or minutes before the primary calving event. During the primary event, failure results in the production of a large iceberg that separates from the glacier and enters the ocean. Secondary events during which additional icebergs are calved can follow hours or days later. All of these events occur on time scales of minutes, but are spread out from one another over minutes to days. While remote sensing has revolutionized the field of glaciology, providing unprecedented observations and insights, it nonetheless suffers a shortcoming in the context of understanding the calving process. Specifically, high frequency repeat observations are not possible. To circumvent this shortcoming, we put together a comprehensive plan of on-the-ground, on-the-glacier, and in-the-ocean instrumentation to be deployed at the calving front of a Greenland tidewater glacier. We caution that our observations are from a single glacier, and may not generalize to others.

We sought to answer the following questions:

- *How does the strain (rate) field evolve during calving?*
- *Does calving lead to acceleration of the glacier?*
- *Is there a relation between calving and cliff height?*
- *Or calving and water depth?*
- *Can seismic signals from a close-array locate a calving event?*
- *Does atmospheric variability play a role in calving?*
- *Do ocean waves trigger calving?*

Based on scientific and logistical considerations, we chose Helheim Glacier in east Greenland as our study site (Fig. 1). The observations we report and the conclusions we draw represent a pilot effort, essentially demonstrating the utility of combining certain glaciological, oceanographic, and meteorological observations relevant to the calving process. Most importantly, our pilot effort demonstrates the potential for a deeper understanding of calving to be achieved through future similar, sustained in-situ observations.

The outline of this paper is as follows. The next section reviews existing calving theories and parameterizations and how they motivate our field work. The field work section describes our instrumentation and presents our key observations. The final section summarizes our findings and points to future field and modeling activities related to calving.

2 EXISTING CALVING PARAMETERIZATIONS

The overarching goal of our work is to develop a viable parametrization of calving that can be used in global climate models to better project sea-level change arising from Greenland mass loss. A simple, universal calving law might be illusory, and many different calving mechanisms likely exist [Van der Veen, 2002; Benn et al., 2007; Vieli & Nick, 2011]. To aid the reader in understanding the current state-of-the-art in calving models, we provide some background on current theory, and how various existing parameterizations bear on the types of observations we undertake. Of course, not all physical variables are easily observable, particularly those at depth in the glacier, and this limits to some degree our field observation possibilities. A number of mechanisms have been discussed in the literature as triggers for glacier front calving (Fig. 2), and are presented below. Calving may be dominated by any one of these mechanisms, or a combination, or by mechanisms yet not envisaged.

The interaction of calving with the motion of the glacier itself is intricate, and raises the question: does calving cause change in the glacier flow field, vice-versa, or both? Some researchers point out that calving leads to a reduction in the backstress and therefore an acceleration of the glacier, considered over many calving events [De Angelis & Skvarca, 2003; Howat et al., 2005]. On the scale of individual calving events this also appears to be the case [Amundson et al, 2008; Nettles et al, 2008]. A contrasting view is that calving is a consequence of changes in glacier motion [Van der Veen, 2002]. Computer simulations of Helheim Glacier [Nick et al., 2009] and a force balance analysis [Howat et al., 2005] suggest that the recently-observed glacier acceleration, thinning, and retreat originate at the calving terminus and then propagate upstream due to changes in geometry and driving stress. These findings motivate us to observe motions at the calving front, and to ascertain if changes further upstream occur before or after calving.

Calving and associated glacial earthquakes have been previously observed at Helheim Glacier [Nettles et al., 2008]. They deployed a dozen GPS receivers spanning an along-flow distance of about 20 km. The global seismographic network [GSN, 2014] was also used to monitor glacial earthquakes, while the calving front position was estimated based on remote-sensing images. Their data show abrupt increases in the along-flow velocity that correlate well with the times of calving and glacial earthquakes. A more recent study focused on glacial earthquakes at Jakobshavn Glacier on the west coast of Greenland. Sergeant et al. [2016] used broadband seismometers to invert for the force history of the calving glacier on the solid earth. Their analysis shows that seismic data provide a unique dynamical constraint that may in future be helpful to discriminate between different mechanical models of calving events, and to quantify associated rheological parameters. These seismic observations, along with others taken by Bartholomeus et al. [2015] relating to seismic activity brought on by subglacial discharge, inspire us to include a broadband seismic array deployed near the calving front to more precisely locate calving events.

Glacier calving is thought to be a consequence of the glacier experiencing a critical failure stress. The stress field experienced by a glacier is often modeled as being

proportional to the strain rate field, influenced by nonlinear viscosity. Thus, the stretching rate of a glacier is another putative precursor to calving. Longitudinal stretching in the along-flow horizontal direction [Benn et al., 2007, Alley et al., 2008; Amundsen & Truffer, 2010], if it reaches a critical-strain rate [Pralong & Funk, 2005], can lead to ice failure and calving. Longitudinal-stretching in both horizontal directions [Levermann et al., 2012] has also been considered. Benn et al. [2007] argue that the longitudinal-strain rate is the first-order control as it determines crevasse depth, with crevassing viewed as a precursor to calving. Parameterization of calving based on longitudinal-strain rate has been implemented in a two-dimensional ice-flow model [Nick et al., 2010] and a three-dimensional full-Stokes model [Otero et al., 2010]. Nick et al. [2010] indicate that this parameterization produces a seasonal cycle that compares well with observations, but also point out that details relating to choice of calving criterion can affect the result. Other researchers have considered including damage mechanics, in addition to linear strain and elastic mechanics, to arrive at a calving model [Krug et al, 2014]. Newly available radar instrumentation (Terrestrial Radar Interferometry, or TRI, described below) allows us to make rapid repeat observations of glacier displacements, in turn allowing velocity and strain rate estimates, over the entire front of Helheim Glacier.

Researchers have proposed empirical relations for calving that involve a single parameter, such as water depth [Brown et al., 1982]. In a similar fashion, height-above-buoyancy, in which the ice thickness at the terminus is assumed to reach only a maximum or critical height-above-buoyancy [Meier & Post, 1987; Bassis & Walker, 2012], has also been proposed. However, these relationships can vary between glaciers and can even change with time for a single glacier [Van der Veen, 2002]. Additionally, we must consider the possibility that a floatation criterion, i.e. a combination of water depth and cliff height, may play an important role in calving. With that caveat notwithstanding, we observe water depth and height-above-buoyancy evolution to ascertain their potential relevance to calving.

Researchers have also questioned whether or not ocean waves in the fjords abutting the glacier front play a role in calving [MacAyeal et al., 2009]. Nettles et al. [2008] reported that small tsunamis followed the glacial earthquakes, and attributed them to large pieces of ice falling into the fjord during calving. In contrast, and not necessarily in contradiction, there is also evidence to suggest ocean swell triggers glacier calving [Bromirski et al., 2010]. Ocean tides certainly have an impact on the motion of the glacier near the calving front as observed using TRI [Voytenko et al., 2015b], but whether or not they play an important role in calving is not yet clear. To gain some insight into the role of ocean tsunamis and ocean tides on calving, we deploy an array of seafloor high-sampling frequency pressure meters (i.e. tsunameters), not far from the glacier front.

A physical feature that may play a role in calving is the mélange of sea ice and icebergs that exists seaward of the calving front. The mélange may have sufficient mechanical strength to hold back the glacier front and thus influence calving, as appears to be the case on seasonal timescales at different glaciers in Western Greenland [Amundson et al., 2010; Walter et al., 2012]. Amundson et al. [2010] deployed cameras, GPS, seismometers (on bedrock), audio recorders, and water pressure sensors near the calving front of Jakobshavn, another Greenland outlet glacier, observing large increases

in the velocity of the mélange at the onset of calving events. Before a calving event, the mélange advanced at 40 m/day, but reached much higher speeds for several minutes during a calving event. Peters et al. [2015] used a TRI to investigate the behaviour of the mélange during calving. Voytenko et al. [2015b] described the use of near-field TRI observations to measure tidal fluctuations. Our field campaign correspondingly includes TRI observations of the mélange in front of Helheim.

Crevassing is an important precursor to calving. An extensive review of the formation of crevasses, including basal crevasses and hydrofracturing, is presented in Colgan et al [2016]. Observations of calving at Helheim Glacier using stereo photogrammetry suggested that a basal crevasse may be a key ingredient in establishing the onset and location of calving [James et al., 2014]. Murray et al. [2015] also found basal crevassing as a likely precursor to calving at Helheim Glacier. TRI observations at Jakobshavn Glacier in West Greenland came to a similar conclusion [Xie et al., 2016]. These studies point out that undercutting of the glacier front by ocean melt might lead to weakening of basal ice, and with buoyant flexure, may force the opening of basal crevasses. Direct observations of this process have not been made, and remain extremely challenging.

Another avenue by which the calving process may be driven is that of subaqueous ocean driven melting at the terminus. A review of the relevance of this process is provided by Truffer and Motyka [2016]. It is possible that mechanical calving is a passive reaction to ocean-driven melt [O'Leary and Christofferson, 2013]. Subaqueous melting is difficult to observe, and is not included in the current suite of observations, but will hopefully be included in future campaigns.

Surface or near-surface meltwater may be a preconditioner for calving disintegration of an ice shelf, with hydro-fracturing as a possible mechanism [Scambos et al., 2009]. Recent simulations of Antarctic change have invoked hydrofracturing [DeConto & Pollard, 2015]. The underlying physics is the fact that water is denser than ice, and a buildup of water in surface crevasses can lead to a catastrophic failure of the ice through pressure. For an outlet glacier such as Helheim, having a heavily crevassed surface, it may be more appropriate to consider calving as related to water-filled crevasses [Benn et al., 2007]. We use an automated weather station to record glacier surface temperature, and photos of the glacier surface to attempt to evaluate the role of surface hydrofracturing in calving.

To make a meaningful projection of outlet glacier change, Nick et al. [2010] conclude that ‘a realistic parameterization for the process of calving is crucial.' We argue that a comprehensive observational database of calving is needed for any such parameterization. There likely exist different types of calving, and only through observation of many calving events, at many different outlet glaciers will a comprehensive understanding emerge. In the next section, we describe in detail the instrumentation we deploy to observe calving, and its arrangement near the Helheim calving front. While our pilot deployment was for a relatively short period of time, capturing a single calving event, we suggest that sustained observations and the creation of a large, publicly accessible database of many calving events could lead to a realistic and usable parameterization of calving for Greenland tidewater glaciers.

3 FIELD CAMPAIGN

During a one-week period in August 2014 we deployed a suite of in-situ instrumentation (Fig. 3) to observe glacier behavior before, during, and after a calving event. Our instrumentation included: an on-land terrestrial radar interferometer (TRI), on-land broadband seismometers, an automated weather station (AWS); on-ice GPS receivers, on-ice seismometers; and an in-ocean tsunameter array. We were fortunate in that a major calving event occurred during our one-week observational period.

The TRI mapped the evolution of the displacement field of the glacier surface and its elevation both upstream of the front and downstream over the mélange, at two-minute intervals. These measurements were sustained over the entire week. The on-ice GPS instruments recorded three-dimensional motion of the glacier along a flow band. We simultaneously observed seismic activity in the glacier from a set of broadband seismometers that were collocated on the glacier with the GPS, as well as two additional broadband seismometers located on the land adjacent to the calving front. Ocean wave disturbances in the adjacent fjord were monitored from a nearby tsunameter array. Finally, we visually recorded calving events using a time-lapse camera at the nearby AWS, which recorded temperature, humidity, solar and infrared radiation, and wind.

3.1 TRI BACKGROUND

The centerpiece of our field instrumentation is a TRI. A review of the TRI technique is given by Caduff et al. [2015]. Glaciological applications are discussed in Werner et al. [2008], Riesen et al., [2011], and Voytenko et al. [2015a]. We first used TRI at Helheim Glacier during August 2013, observing tidal variability of the glacier front velocity [Voytenko et al., 2015b]. We have also deployed TRI at Jakobshavn, on Greenland's west coast, in June 2015. That deployment was also fortunate to capture calving, and here we draw a similar conclusion to that work, explicitly, that calving may be a multi-day process made up of discrete, punctuated events [Xie et al., 2016].

Satellite-based Interferometric Synthetic Aperture Radar (InSAR) has been available for several decades [Rodriguez and Martin, 1992; Goldstein, 1993; Rignot 1998; Joughin et al., 1999]. A ground-based interferometric radar approach such as TRI offer significant advantages over both satellite observations and ground-based GPS in terms of spatial and temporal resolution. TRI generates displacement, velocity, and elevation updates every few minutes, over wide swaths that can extend ~10 km in any direction. TRI avoids the temporal aliasing of time-varying processes inherent in satellite-based observations (where samples are typically collected every few days), while delivering spatial observations that are orders of magnitude better than sparse GPS networks. While TRI's interferometric observations of displacement and velocity are inherently scalar (it measures only the component of motion in the radar's line-of-sight direction), feature tracking can be employed to obtain two-dimensional velocity vectors with updates of several hours or less, depending on glacier speed [Peters et al. 2015; Xie et al., 2016].

The commercial TRI instrument that we used is an interferometric, Ku-band (1.74 cm wavelength), real-aperture radar that provides high-resolution intensity and phase images [GAMMA, 2016]. Operating at 17.2 GHz, instrument displacement sensitivity is better than 1 mm [Werner et al., 2008]. The instrument has a nominal range resolution of 0.75 m, and an azimuth resolution of 7.5 m at a distance of 1 km, which decreases linearly with distance. The radar has one transmitting antenna and two receiving antennas, typically separated by 25 cm baseline, positioned on a rotating frame (Fig. 4a). The radar takes approximately two minutes to scan data from a 150-degree arc. Consecutive interferograms in time from one transmitting-receiving antenna pair are used to define the velocity. The two receiving antennas provide some redundancy, and if both are operating, they allow repeat mapping of glacier elevation to a vertical precision of about 3 m at 2 km distance [Strozzi et al., 2012]. We use the ISP/DIFF/LAT [2016] software package to process the raw data into finished products. The combination of displacement, velocity, velocity change, elevation, and elevation change via rapid updates provides a powerful tool for calving studies.

Long-term TRI deployments have not yet found widespread use in glaciology, perhaps due to the instrument's cost, relative fragility and power requirements, which can be challenging in the polar environment. We are working to remedy this situation, and in summer 2016 obtained one month of continuous, unattended TRI observations at Helheim. Eventually we hope to observe calving at Helheim Glacier through its entire annual cycle.

To provide the reader with a sense of the kind of data product that TRI can produce, see Fig. S1 in Supp. which shows a typical velocity field for Helheim from our TRI data using feature tracking and overlaying a coincident elevation field. The flow of the glacier in this instance is clearly plug-like, with shearing isolated to relatively thin basal and lateral boundary layers, so that the most important strain rate is longitudinal. In future deployments, we hope to deploy two radars in order to acquire rapid interferometric updates to the velocity field, in stereo. This is useful, as a single radar can only provide one component of velocity, while two can provide both components in the horizontal plane.

3.2 TRI CALVING DETECTION

Although TRI has been typically used to determine relatively slowly-evolving surface characteristics of glaciers such as tidal response [e.g. Voytenko et al., 2015b], TRI data can also be used to examine surface areas experiencing rapid changes [e.g., Xie et al., 2016]. Evaluating the line-of-sight displacements of individual pixels near the calving front during the August 2014 TRI deployment (Fig. S2 in Supp.) reveals a decrease in glacier velocity coincident with the primary calving event at 06:37 UTC on August 12. A secondary calving event only affected a portion of the southern trunk approximately one day later, at 11:31 UTC on August 13. Putting together the observations for the entire TRI scan area before, during, and after the primary calving event (Fig. 5) reveals some of the complexity of the calving process. The initial glacier front peeled back in a multi-step process. From radar intensity images, we can evaluate the position of the calving front

and observe its multi-step retreat (Fig. S3 in Supp.).

A useful metric for surface change can be derived from interferometric correlation, which measures the similarity of scattering characteristics between consecutive radar images (a high correlation implies that the surface is not changing). This metric is typically used to judge phase quality for interferometric phase unwrapping. Here, we use maps of interferometric correlation coefficients between successive two-minute images to determine periods of rapid surface change related to calving. Although the primary event took place at 06:37 UTC on August 12, we observed a strong drop in correlation around 05:46 UTC (approximately an hour before the primary calving event) along a linear, crack-like, surface expression about 400 m upstream of the terminus (Fig. 5, red dots, and Fig. S4 in Supp.). The location of this failure surface also marks the post-calving terminus position. These observations do not necessarily document the true start of the calving process, which may begin days in advance of the primary calving event [James et al., 2014; Xie et al., 2016]. Instead, the precursor event suggests the onset of rapid change in the glacier surface.

We evaluated the strain rate field over the northern trunk of the glacier by spatial differencing (in the horizontal direction) TRI velocity maps, adjusted to match the approximate direction of flow (Fig. S5 in Supp.; and Voytenko et al. [2015a]). The velocity maps were taken from 12 hours before the primary event, around the time of the main event, and 12 hours after to match the tidal phase. Close to the northern trunk, 12 hours before and shortly before calving, the ice front experienced increased strain rates (extension), while the mélange was consistently under compression. We are unable to deduce from this if the glacier reached a critical strain rate, but there is suggestion that changes in strain rate occur well prior to calving.

TRI can produce rapid-update digital elevation maps (DEM) of the Helheim Glacier. The accuracy of the DEM is estimated to be approximately three meters, and while not suitable to discern subtler vertical motions of the glacier, it can certainly detect larger features, such as calving. From an evaluation of the ice front height prior to calving with that after calving (Fig. 6 and Fig. S6 in Supp.) we observe that prior to calving, the cliff reached approximately 100 m in height, and then failed. This observation is roughly in accord with the theoretical failure criteria provided by Bassis and Walker [2011].

From these TRI observations, we henceforth argue calving to be a process, spanning several days, stitched together by singular events, such as noted above, rather than a singular, short minute-scale event.

3.3 GPS

GPS devices measure ground motion in three dimensions, at higher frequency (period < 1 min) and in greater precision (centimeter-level) than TRI. Moreover, TRI usually only provides a single component of motion (the projection of the true velocity vector onto the look vector of the TRI), whereas GPS data determine displacement in three dimensions. A shortcoming, however, is that GPS receivers can in general only be deployed at a handful of locations, and thus yield spatially-sparse observations, while TRI provides

effectively millions of measurements every few minutes.

To monitor higher-frequency (period <1 min) glacier motion, we installed six GPS stations (Fig. 4c) along a central flowline on the northern trunk of the glacier. All GPS sites were deployed early on August 9, 2014 and retrieved later on August 15, 2014. One GPS site ceased recording a few hours after deployment due to an internal fault and a second site failed on the morning of August 11, 2014, after the anchor system melted out of the ice. Each site consisted of dual-frequency receiver (Trimble NetRS 5700 with Trimble Zephyr Geodetic antennas), which collected moderate-rate (1 Hz) GPS data. Positions were determined using differential carrier phase positioning [Chen, 1998] relative to a permanent, fixed GPS receiver at the nearby town of Kulusuk (~100 km away). Horizontal and vertical uncertainties are approximately 5 and 10 cm, respectively. Geodetic solutions were transformed to a northern hemisphere polar stereographic projection centered on Greenland (origin at 90°N, 45°W; standard parallel of 70°N; referenced to the WGS84 ellipsoid; EPSG 3413) for distance and speed calculations.

GPS-derived glacier speeds vary from ~12.5 m/d to ~18.5 m/d (Fig. 7). The site nearest the calving front has the highest speed, at ~18.5 m/d with variations of ~1 m/d. The upstream sites record motion of roughly the same speed (~12.5 to 14 m/d) and character despite being separated by several kilometers, being installed in areas of differing surface slopes, and being subject to differing amounts of surface melt. All GPS sites exhibit diurnal fluctuations in speed. The timing of the daily speed peak (just prior to midnight UTC) and its undamped character at the upstream sites suggests that this daily speed peak may be the result of surface meltwater enhancing basal lubrication, and thus increasing sliding, as has been observed elsewhere on the Greenland Ice Sheet [Shepherd et al., 2009]. The site nearest the calving front, also exhibits a subtler, secondary peak (at ~1200 UTC, just before local low tide) that is not observed at the upstream sites, which could be related to tidal forcing, also inferred from TRI data [Voytenko et al., 2015b].

Glacier motion (speed and character) at the GPS sites remained unchanged after the primary calving event. Following the secondary calving event, however, speed increased at all GPS sites by ~1 m/d at the near-calving front site and ~0.5 m/d at the upstream sites. Speed peaked approximately one day after the secondary calving event and speeds returned to their pre-calving values by ~1200 UTC on August 15, 2014. The low-frequency (daily or longer) character of the post-calving speed peak appears to be roughly symmetrical. The higher-frequency speed fluctuations are temporarily interrupted at the upstream sites, becoming similar to that near the calving front, which suggests that that glacier may temporarily partially decouple from the bed following the calving event, or that stresses are more efficiently transferred upstream for a ~2-day period following calving.

Our GPS data suggest that the upstream effects of calving are limited until a full-width failure occurs of both the northern and southern trunks, indicating that even a relatively small portion of the glacier, in this case the southernmost trunk (~1.5 km wide), can provide significant backstress. This backstress might be redistributed to the remaining intact portion of the glacier following the larger, primary calving event. The post-calving

glacier motion perturbation is also temporary, as glacier speed appears to return to its pre-calving values and character within two days of the termination of the calving process.

3.4 PASSIVE SEISMOLOGY

Seismometers can provide ground velocity in three components, by measuring accelerations. We used broadband instruments, which cover a wide range of frequencies (well below 1 Hz), allowing observation of glacier and land velocity at a much higher rate than our GPS or TRI instruments. The benefit of installing seismometers on the glacier is that they are sensitive to icequake (high frequency cracking of the glacier) and sudden slip events (short duration increases well above background speeds). The advantage of installing on nearby land is that the stations can be utilized for a much longer period of time (several years). We established on-land sites on a rolling basis over the last several years (Fig. 4d) with one site in August 2012 (HEL1 – Nanometrics Trillium 120), another in August 2013 (HEL2 – Nanometrics Trillium 240), and two others in August 2014 (HEL3 and HEL4 – Nanometrics Trillium 240). These broadband seismometers continue to operate. On the glacier, we established a seismic array in the vicinity of the Helheim calving front, along a flow line on the glacier (Nanometrics Trillium Compact Posthole) (Fig. 4c) co-located with the GPS array mentioned above, and also on land (Nanometrics Trillium 120), on opposite sides of the calving front (Fig. 4d).

When a calving event happens, the seismic waves that emanate from the glacial fracture take different amounts of time to reach each seismic station, depending on the distance from the fracture to the station. It is then a straightforward calculation to invert for location given a standard velocity of seismic waves through ice and travel time to each station. Surprisingly, we found that the calving energy propagated at a much slower speed (~1,600 m/s) than the typical compressional wave speed in ice (3,800 m/s). We developed a method of determining glacier calving locations using seismic wave arrival times from paired local seismic stations [Mei et al., 2016]. In short, the difference in surface wave arrival times for each pair of stations is used to define a locus (hyperbola) of possible origins. With multiple pairs, this can be used to triangulate the origin of the seismic waves, interpreted as the calving location. Our different approach was motivated by difficulties with traditional seismic location methods that fail due to the emergent nature of calving, which obscures the primary and secondary wave onsets, and the close proximity of the seismometers, which combines body and surface waves into one arrival. As a summary of that previous work, our locations determined from seismic data match the location of calving determined by time-lapse cameras and remote sensing.

On August 12, while camped near the calving front our team was awoken by a sustained, loud rumbling noise. Three of the seismometers, recorded vibrations that occurred during the primary calving event at this moment (Fig. 8). One of the stations was deployed on the glacier surface, while the other two were well above the glacier, on nearby land. From the seismic data collected, we were able to ascertain that the peak of the calving event, the primary in a seismic sense, occurred at 06:37 UTC. Using cross-correlation of the seismic signals, we are able to determine the difference in arrival times, and from this, estimate the calving location. In fact, two different methods are used to

estimate the calving event location, and they produce similar results, indicating the same location on the northern glacier trunk. In the first method, travel times from all three seismic stations are used simultaneously to find the most likely singular point of origin of the calving signal, which is shown as the blue X (Fig. 9). In the second method, seismic stations are used in only a pairwise sense and this results, instead of a point location, an area as shown by the blue triangle (Fig. 9, details in Mei et al [2016]).

From a TRI map of interferometric correlation (see again Fig. 5), we reported a precursor event nearly an hour prior to the primary calving. The formation of this TRI surface expression seems to be related to seismic activity around the same time (Fig. S7 in Supp.). Evidence of precursory activity, from both TRI and seismic, gives us greater confidence in asserting that calving is a process, made up of a number of punctuated events. Calving of large ice masses may be a similar to earthquakes, in that earthquake foreshocks sometimes culminate in much larger earthquakes. We note that there are also several periods of high glaciogenic seismic energy visible on seismograms that do not culminate into a large calving event. Detailed analysis of the high frequency on-ice seismicity is the subject of ongoing study.

Parenthetically, the bedrock elevation of Helheim Glacier indicates that the bedrock is deeper beneath the northern half of the trunk (Fig. 9), a fact that may be linked to where the glacier preferentially calves, suggesting that a glacier grounded on deeper bedrock, or the deeper portions of a calving front, may be more susceptible to calving.

3.5 TSUNAMETERS

Another way to track glacier activity is to monitor nearby ocean waves. These waves can be excited by changes at the glacier front propagating subsequently into the ocean, or vice versa, and thus have the potential to provide complementary information about the calving process.

An array of seafloor moorings was deployed in Sermilik Fjord prior to our field campaign. Tsunameters installed on each mooring were used to detect calving events in the fjord. The tsunameters sampled every four seconds, which allowed for detection of the fast barotropic waves traveling along the fjord. At the time of the primary August 12, 2014 event, two tsunameters were active with their locations shown in Fig.10a. The closer one to the calving front was located about 70 km away at depth of 880 m, and the farther one was 84 km away at depth of 908 m.

A propagating barotropic wave associated with each calving event was detected on both active tsunameters (Fig. 10b). The signal of the primary calving event reached the closest sensor between 6:51 and 6:53 UTC with amplitude of 10 cm. Approximately 160 seconds later the signal arrived at the farther one. Using a mean propagation speed of calving waves in Sermilik Fjord, a barotropic signal generated at the calving front location takes between 14.7 and 17.1 minutes to reach the closer sensor. This rough calculation suggests the timing of the first calving event to be initiated sometime between 6:34 and 6:39 UTC.

The smaller secondary event reached only one quarter of the amplitude of the primary event and arrived at the closer tsunameter around 11:40 UTC, and at the farther one with 160 seconds lag again. The tsunameter data thus estimate the second event to be initiated between 11:31 and 11:36 UTC, August 13.

The spectral and propagation characteristics of these waves are consistent with those of other calving generated waves observed in Sermilik Fjord [Vaňková & Holland, 2016]. In the cited study, a numerical model suggested that the effect of calving on the ocean is equivalent to a damped oscillator boundary forcing with oscillation period between 5 to 10 minutes and damping time scale of 10 minutes. We conclude from our ocean-based observations that in the instance of the calving events we observed in August, 2014, calving created a wave response in the ocean, and not vice versa. We also note that going forward, sea-floor tsunameter arrays are an effective way to monitor calving of an outlet glacier. Such arrays can be placed at significant distance from the calving front, e.g. tens of kilometer, and thus can be safely deployed away from the calving front and the mélange. Broadband seismic stations at costal locations may also be capable of providing similar information [Amundsen et al, 2012].

3.6 AWS

A cursory analysis of our AWS data (air temperature, radiation, wind, and precipitation) did not reveal any obvious link to the observed calving events during our week-long observation period, which is perhaps not surprising. From our AWS time-lapse cameras (Fig. 3.11), we know the precise position of the calving front before and after the various calving events. It is reassuring to find that the locus of the calving energy as determined from the seismic data (Fig. 3.9) is located near the calving front as revealed by the camera images (Fig. 3.11).

The northern and southern trunks of the Helheim Glacier meet along a medial moraine, evident in Fig 3.11 as a dark line consisting of rock and dust following along a flow line. This suture zone, where two glacier streams meet, likely has a different structural makeup than the ice elsewhere in either trunk, and we speculate that it plays a role in the nature of the calving we witnessed (i.e. the secondary event occurred only over the southern trunk) [Walker et al., 2015].

Anecdotally, while flying over the glacier several days before the calving events we noticed a significant amount of water collected in surface crevasses. Several days after the calving events, we again flew over the glacier and noticed that most of the surface water had disappeared. Our AWS cameras were not adequately positioned to show the surface water and thus we are unable to say when the water drained and if it had any possible relation to the calving events.

Our AWS camera was in operation prior to our field campaign and time-lapse over the preceding year shows the aperiodic nature of the calving events at Helheim (Fig. S8 in Supp.). It is evident from year-long time-lapse cameras, that the Helheim Glacier generally advances in winter and retreats in summer, highlighting the fact that there is an atmospheric influence on calving. The mechanism by which the atmosphere impacts

seasonal calving remains unclear, requiring further observational data.

4 TOWARD PARAMETERIZED CALVING

As mentioned earlier, our overarching goal is to develop a parameterization of calving. A practical first step to this goal is to build a detailed process model, using theory motivated by observations that can accurately simulate aspects of the calving process (see again Figs. 5, 6). Such a process model is likely not suitable for use in a large-scale, long-simulation climate model, but can serve to guide the construction of a simplified parameterization of calving to be used in a climate model. This parameterization goal is well beyond the scope of the present work, in which we are only reporting on one observation of calving, and our first steps towards detailed modeling of the phenomenon.

Glacier flow can only be accurately modeled provided one knows the rheology of the ice, i.e. the relation between the strain rate and stress fields. The viscous rheology appropriate to a slowly flowing glacier undergoing creep is relatively well known [Glen, 1958], as is the elastic rheology appropriate to bending [Timoshenko & Goodier, 1970]. The plastic rheology that is perhaps appropriate to a fast moving glacier that is undergoing fracturing and calving, such as Helheim Glacier, is unknown. Current generation glacier models do not simulate calving in a realistic manner but progress is being made by considering damage mechanics [e.g. Krug et al, 2014]. While such models do describe the viscous and elastic behavior of glaciers based on an assumed relation between strain (or strain rate) and stress, they do not yet describe the failure associated with plastic flow, which is independent of strain and strain rate, complicating matters greatly. Future modeling advancements, based on observations reported here and elsewhere, should move forward the ability to model the plastic failure stress that glaciers such as Helheim likely undergo. Specifically, our future observational efforts at Helheim will be targeted at providing the data necessary to modify the glacier rheology to include a plastic yield curve. This will be carried out following the analogous theoretical framework, widely used in the sea-ice literature, successful in modeling sea-ice plastic failure [Hibler, 1979].

Based off an existing two-dimensional, along flow line model [Parizek et al., 2013] we have begun to model the stress state of Helheim Glacier. As a starting point we are simulating the viscous and elastic stress fields. When and where a glacier such as Helheim ultimately fails depends not only on its material strength and the many imperfections that limit it, but also on the crack-forming viscous (Fig. 12) and elastic (Fig. S9 in Supp.) differential stress field to which it is subjected as it completes its journey to the ocean. Within a field of crevasses, theory indicates ~320 kPa of tensile stress is necessary to generate new crevasses, with that threshold decreasing to ~30-80 kPa for individual crevasses [van der Veen, 1998]. For a calving event to take place, surface and/or basal crevasses must penetrate the full glacier thickness. In the viscous realm, crevassing often takes place along lateral shear margins, where there are transitions in basal topography and/or drag, and proximal to the ice-front where differences between the glaciostatic and hydrostatic pressures across the interface lead to enhanced deviatoric stresses within the ice that maintain the overall force balance. The glacier surface steepens just downstream of regions with topographic highs and/or enhanced basal drag to drive flow across these features, with the resulting changes in flow speed

leading to tensional longitudinal stresses within the glacier. Furthermore, tensional stresses also develop across an onset region of an ice shelf or ice tongue as basal traction vanishes where the base of the glacier loses contact with the solid earth. Finally, within a few thicknesses or less of a marine-terminating glacier front, the stress state within a glacier also favors failure due to the glaciostatic/hydrostatic pressure imbalance between the glacier front and the combination of air and seawater into which it is flowing (Fig. 12), as well as the tidal flexure of the floating tongue (Fig. S9 in Supp.). At this stage, it is not yet clear from observation if any, some, or all of these detailed factors need be included in a parameterization of calving.

While our modeling effort is currently aimed at a deterministic simulation of calving, as is appropriate in the context of developing a process-oriented understanding of calving, it may turn out in the long run that such a deterministic approach is not feasible in the context of large-scale, long-simulation climate modeling. An alternative approach for a calving parameterization has been to invoke a probability distribution, with calving considered a random event drawn from an underlying distribution [Bassis, 2011]. The empirical relationships or probability distributions appear to depend strongly on the characteristics of a specific outlet glacier (bed slope, the presence of an ice shelf, thickness above flotation, etc.). While we here present observations of just one calving event and seek in the future to collect many more, there may be merit in the ultimate parameterization of calving as a random event. Clearly, a large database of calving events is required in order to build a viable probability distribution to give this approach a significant foundation. This is also one of our long term goals.

While calving has obvious relevance to glaciology, it is also germane to oceanography albeit indirectly. This is particularly so in the context of freshwater release arising from melting of Greenland's icebergs into the North Atlantic Ocean and their impact on ocean stratification, and thus open-ocean convection and deep-water formation [Weijier et al., 2012; Boning et al, 2016]. It is important to understand where large icebergs go and where they melt, but even to arrive there it is important as a starting point to know where icebergs are produced and what is their size distribution. The type of calving parameterization we seek here through our future glaciological modeling efforts feeds directly into this principal need in oceanographic modeling.

5 SUMMARY

Using a suite of instrumentation, we sought to collect data that would help us gain insight into key questions relating to calving. Here, we reiterate these questions, and summarize our responses.

- *How does the strain (rate) field evolve during calving?*

  Through TRI measurements, we observed a variability of the horizontal strain rate 12 hours before, during, and 12 hours after the primary calving event. The calving detected August 12-13, consisted of a precursor, primary, and secondary events. Well prior to calving, the glacier strained in a fashion showing larger strain rates near the calving front, and less so upstream, and less so after the calving. The first strong indication of calving occurred approximately one hour prior to the primary calving event (based on interferometric correlation measurements), with rapid changes in the surface observed along a transverse front that was destined to become the new terminus.

- *Does calving lead to acceleration of the glacier?*

  From GPS near the glacier front, along a flowline of the northern trunk, a significant increase in speed was only detected following the secondary calving event, and not the primary. Similar behavior was seen in the TRI. This post-calving increase in speed vanished after an additional two days, as the glacier readjusted to its pre-calving motion.

- *Is there a relation between calving and cliff height?*

  Fairly consistent with existing theoretical estimates, we noted that the cliff height of the pre-calving ice front was approximately 100 m, and the post-calving height was 80 m. This lends some sustenance to the theoretical construct that only a certain height of cliff can be mechanically supported by intrinsic glacier strength.

- *Or calving and water depth?*

  We detected calving that occurred first along the deeper northern trunk of the glacier, and secondly along the shallower southern trunk. This offers some backing to the theoretical concept that glaciers in deeper water are more likely to calve than shallow water, again a mechanical support argument. It should also be pointed out that the combination of cliff height and water depth (i.e. closeness to floatation) may also play a role, but is not investigated here.

- *Can seismic signals from a close-array locate a calving event?*

  Using triangulation from combined on-glacier and on-land broadband seismometers, and corroborated by AWS cameras and TRI, we found that

seismically determined calving location coincided with the post-calving terminus. Moreover, the seismic array pointed to a particular portion of the ice front as being the most active area, coinciding with the deepest bed at the front.

- *Does atmospheric variability play a role in calving?*

  Our AWS instruments did not record any atmospheric properties that showed a direct bearing on the witnessed calving events. As changes in upglacier surface meltwater ponding within crevasses were observed, this does not rule out the impact of atmospheric variability, particularly on the longer seasonal time scale, on glacier calving.

- *Do ocean waves trigger calving?*

  For the discrete calving events we observed, it is unequivocal that the glacier calving preceded the ocean tsunami response. This suggests that high-frequency ocean swell did not play a role in triggering calving, and in fact just the opposite. This does not rule out ocean tides (high/low or spring/neap) in playing a part in this calving event as tides over a long time period may promote wear on the many fracture surfaces and ultimately promote weakening.

In summary, this pilot study has sought an improved understanding of calving at Helheim Glacier, and Greenland tidewater glaciers in general. We have seen that among important observations needed to understand calving are the evolution of the height of the cliff at the glacier front as well as the depth of the ocean, and the strain rate near the calving front. There are also observations from inside or beneath the glacier, such as the occurrence of basal crevasses, that we do not yet have the capability to observe, but are likely important. Our observations reinforce the idea that calving is a cumulative process, made up of a number of discrete events, occurring over a number of days. We again caution that our observations are from a single glacier, and may not generalize to others. Whether or not the observed, cumulative nature of calving will play a role in the parameterization of calving remains a question for future study. The noted temporal span of the calving process may, for instance, have ramifications for the time-stepping of a model parametrization of the process. Continued development of numerical models, deterministic or probabilistic, with realistic glacier failure criteria built on rheology consistent with field observations, may ultimately lead to usable parameterizations that can make future sea-level projections more robust.

ACKOWLEDGMENTS

We are grateful to the support provided by the NASA JPL Oceans Melting Greenland (OMG) grant to DMH at New York University. Additional support from New York University Abu Dhabi (NYUAD) through grant G1204 to DMH and DH in the Center for Global Sea Level Change (CSLC) is recognized. The USA National Science Foundation provided support to DMH and DH via ARC-1304137, and to BRP via PLR-1443190, ANT-0424589, and AGS-1338832. The National Aeronautics and Space Administration provided support to BRP via NNX15AH84G and to RTW via NNX12AD03A. Air Greenland is acknowledged for providing superb helicopter support over the glacier, Mr. Brian Rougeux for field safety operations, and Captain Sigurdur Petursson for ocean tasks.

REFERENCES

Alley, R.B., H.J. Horgan, I. Joughin, K.M. Cuffey, T.K. Dupont, B.R. Parizek, S. Anandakrishnan, & J. Bassis (2008), A simple law for ice-shelf calving. *Science* 322, no. 5906, 1344-1344.

Amundson, J. M., & Truffer, M. (2010). A unifying framework for iceberg-calving models. *Journal of Glaciology*, 56(199), 822-830.

Amundson, J. M., Truffer, M., Lüthi, M. P., Fahnestock, M., West, M., & Motyka, R. J. (2008). Glacier, fjord, and seismic response to recent large calving events, Jakobshavn Isbræ, Greenland. *Geophysical Research Letters*, 35(22).

Amundson, J. M., Clinton, J. F., Fahnestock, M., Truffer, M., Lüthi, M. P., & Motyka, R. J. (2012). Observing calving-generated ocean waves with coastal broadband seismometers, Jakobshavn Isbræ, Greenland. Annals of Glaciology, 53(60), 79-84.

Amundson, J. M., M. Fahnestock, M. Truffer, J. Brown, M. P. Luthi, & R. J. Motyka (2010). Ice mélange dynamics and implications for terminus stability, Jakobshavn Isbræ, Greenland*. J. Geophys. Res*., 115, F01005, doi:10.1029/2009JF001405.

Bartholomaus, T. C., Amundson, J. M., Walter, J. I., O'Neel, S., West, M. E., & Larsen, C. F. (2015). Subglacial discharge at tidewater glaciers revealed by seismic tremor. *Geophysical Research Letters,* 42(15), 6391-6398.

Bassis, J. N. (2011), The statistical physics of iceberg calving and the emergence of universal calving laws. *Journal of Glaciology*, 57(201), 3-16.

Bassis, J. N., and C.C. Walker (2011). Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice. In *Proc. R. Soc. A* (p. rspa20110422). The Royal Society.

Benn, D.I., C.R. Warren, & R.H Mottram (2007). Calving processes and the dynamics of calving glaciers. *Earth-Science Reviews*, 82, 143-179, doi:10.1016/j.earscirev.2007.02.002.

Böning, C. W., Behrens, E., Biastoch, A., Getzlaff, K., & Bamber, J. L. (2016). Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nature Geoscience*.

Bromirski, P. D., Sergienko, O. V., & MacAyeal, D. R. (2010), Transoceanic infragravity waves impacting Antarctic ice shelves. *Geophysical Research Letters*, 37(2).

Brown, C.S., M.F. Meier, & A. Post (1982). Calving speed of Alaska tidewater glaciers with applications to the Columbia Glacier, Alaska. *U.S. Geological Survey Professional Paper*, 1258-C. 13 pp.

Caduff, R., F. Schlunegger, A. Kos, & A. Wiesmann (2015). A review of terrestrial radar interferometry for measuring surface change in the geosciences. *Earth Surface Processes and Landforms*, 40(2), 208-228.

Chen, G. (1998), GPS kinematics positioning for airborne laser altimetry at Long Valley, California, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA, USA.

Colgan, W., H. Rajaram, W. Abdalati, C. McCutchan, R. Mottram, M. Moussavi, & S. Grigsby (2016). Glacier Crevasses: Observations, Models and Mass Balance Implications. *Reviews of Geophysics*, 10.1002/2015RG000504.

De Angelis, H., & P. Skvarca (2003). Glacier surge after ice shelf collapse. *Science*, 299, 5612, 1560–1562, doi:10.1126/science.1077987.

DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. *Nature*, 531(7596), 591-597.

GAMMA (2016). GAMMA Portable Radar Interferometer. http://www.gamma-rs.ch/rud/microwave-hardware/gpri.html

Goldstein, R.M., H. Engelhardt, W.B. Kamb, & R.M. Frohlich (1993). Satellite radar interferometry for monitoring ice sheet motion: Application to an Antarctic ice stream. *Science*, 262, 1525–1530.

Glen, J. W. (1958), The flow law of ice: A discussion of the assumptions made in glacier theory, their experimental foundations and consequences. *IASH Publ*, 47, 171-183.

GSN (2014), Global Seismographic Network, http://www.iris.edu/hq/programs/gsn

Holland, D. M., R. H. Thomas, B. DeYoung, M. H. Ribergaard, & B. Lyberth (2008). Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. *Nat. Geosci*., 1, 659– 664, doi:10.1038/ngeo316.

Howat, I. M., I. Joughin, S. Tulaczyk, & S. Gogineni (2005). Rapid retreat and acceleration of Helheim glacier, east Greenland. *Geophys. Res. Lett*., 32, L22502, doi:10.1029/2005GL024737.

Howat I. M., A. Negrete, and B. E. Smith, (2014) The Greenland Ice Mapping Project (GIMP) land classification and surface elevation datasets. *The Cryosphere*, 8, 1509-1518, doi:10.5194/tc-8-1509-2014.

IPCC (2007). Climate Change 2007: The Physical Science Basis. http://www.ipcc.ch

IPCC (2013). Climate Change 2013: The Physical Science Basis. http://www.climatechange2013.org

ISP/DIFF/LAT (2016), GAMMA Processing Software: Interferometric SAR Processor (ISP), Differential Interferometry and Geocoding package (DIFF), and Land Application Tools (LAT), http://www.gamma-rs.ch/no_cache/software.html

James, T. D., Murray, T., Selmes, N., Scharrer, K., & O'Leary, M. (2014). Buoyant flexure and basal crevassing in dynamic mass loss at Helheim Glacier. *Nature Geoscience*, 7(8), 593-596.

Joughin, I, W. Abdalati, & M. Fahnestock (2004). Large fluctuations in speed on Greenland's Jakobshavn Isbrae glacier. *Nature*, 432, 608–610, doi:10.1038/nature03130.

Joughin, I., I.M. Howat, R.B. Alley, G. Ekstrom, M. Fahnestock, T. Moon, M. Nettles, M. Truffer, & V.C. Tsai (2008). Ice-front variation and tidewater behavior on Helheim and Kangerdlugssuaq Glaciers, Greenland. *J. Geophys. Res*., 113, F01004, doi:10.1029/2007JF000837.

Joughin, I, R.B. Alley, & D.M. Holland, (2012). Ice sheet response to oceanic forcing. *Science*, 338(6111), pp. 1172-1176 DOI: 10.1126/science.1226481.

Joughin, I., L. Gray, R. Bindschadler, S. Price, D. Morse, C. Hulbe, K. Mattar, & C. Werner (1999), Tributaries of West Antarctic ice streams revealed by RADARSAT interferometry. *Science*, 286, 283–286.

Krug, J., Weiss, J., Gagliardini, O., & Durand, G. (2014). Combining damage and fracture mechanics to model calving. *The Cryosphere*, 8(6), 2101-2117.

Landsat8 (2016), http://landsat.usgs.gov/landsat8.php

Leuschen, C., & Allen, C. (2013). IceBridge MCoRDS L3 Gridded Ice Thickness, Surface, and Bottom,

Version 2, Helheim_2008_2012_Composite. Boulder, Colorado USA: NASA DAAC at the National Snow and Ice Data Center. http://nsidc.org/data/docs/daac/icebridge/irmcr3/

Levermann, A., T. Albrecht, R. Winkelmann, M.A. Martin, M. Haseloff, M., & I. Joughin (2012), Kinematic first-order calving law implies potential for abrupt ice-shelf retreat. *The Cryosphere*, 6(2), 273-286.

Luckman, A., T. Murray, R. de Lange, & E. Hanna (2006). Rapid and synchronous ice-dynamic changes in East Greenland. *Geophys. Res. Lett*., 33, L03503, doi:10.1029/2005GL025428.

MacAyeal, D. R., E. A. Okal, R. C. Aster & J. N. Bassis (2009). Seismic observations of glaciogenic waves (micro-tsunamis) on icebergs and ice shelves. *Journal of Glaciology,* 55(190), 193-206.

Mei, M. J., Holland, D. M., Anandakrishnan, S., & Zheng, T. (2016). A Two-Station Seismic Method to Localize Glacier Calving. *The Cryosphere Discussion,* DOI:10.5194/tc-2016-85

Meier, M. F., & Post, A. (1987). Fast tidewater glaciers. *Journal of Geophysical Research: Solid Earth*, 92(B9), 9051-9058.

Murray, T., Selmes, N., James, T.D., Edwards, S., Martin, I., O'Farrell, T., Aspey, R., Rutt, I., Nettles, M. and Baugé, T., 2015. Dynamics of glacier calving at the ungrounded margin of Helheim Glacier, southeast Greenland. *Journal of Geophysical Research: Earth Surface*, *120*(6), 964-982.

Moon, T., & I. Joughin (2008). Changes in ice front position on Greenland’s outlet glaciers from 1992 to 2007. *J. Geophys. Res*., 113, F02022, doi:10.1029/2007JF000927.

Nettles, M., T. Larsen, P. El´osegui, G. Hamilton, L. Stearns, A. Ahlstrøm, J. Davis, M. Andersen, J. de Juan, & S. Khan (2008), Step-wise changes in glacier flow speed coincide with calving and glacial earthquakes at Helheim Glacier, Greenland. *Geophys. Res. Lett.*, 35 (24), L24,503.

Nick, F. M., A. Vieli, I. M. Howat, & I. Joughin (2009) Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. *Nat. Geosci*., 2, 110– 114, doi:10.1038/NGEO394.

Nick, F. M., C. J. Van der Veen, A. Vieli, & D. I. Benn (2010), A physically based calving model applied to marine outlet glaciers and implications for the glacier dynamics. *J. Glaciol.*, 56 (199), 781-794.

O'Leary, M., & Christoffersen, P. (2013). Calving on tidewater glaciers amplified by submarine frontal melting. *The Cryosphere,* 7(1), 119-128.

Otero, J., F.J. Navarro, C. Martin, M.L. Cuadrado, & M.I. Corcuera (2010). A three-dimensional calving model: numerical experiments on Johnsons Glacier, Livingston Island, Antarctica. *J. Glaciol.*, 56 (196), 200-214.

Peters, I. R., Amundson, J. M., Cassotto, R., Fahnestock, M., Darnell, K. N., Truffer, M., & Zhang, W. W. (2015). Dynamic jamming of iceberg-choked fjords. *Geophysical Research Letters*, 42(4), 1122-1129.

Parizek, B.R., K. Christianson, S. Anandakrishnan, R.B. Alley, R.T. Walker, et al. (2013), Dynamic (in)stability of Thwaites Glacier, West Antarctica. *J. Geophys. Res.-Earth Surface*, 118, doi:10.1002/jgrf.20044 (2013).

Peters, I. R., Amundson, J. M., Cassotto, R., Fahnestock, M., Darnell, K. N., Truffer, M., & Zhang, W. W. (2015). Dynamic jamming of iceberg-choked fjords. *Geophysical Research Letters*, 42(4), 1122-1129.

Pralong, A., & Funk, M. (2005). Dynamic damage model of crevasse opening and application to glacier calving. *Journal of Geophysical Research: Solid Earth* (1978–2012), 110(B1).

Riesen, P., T. Strozzi, A. Bauder, A. Wiesmann, & M. Funk (2011), Short-term surface ice motion variations measured with a ground-based portable real aperture radar interferometer. *J. Glaciology*, 57(201), 53–60.

Rignot, E. (1998). Fast recession of a West Antarctic glacier. Science, 281(5376), 549-551.

Rignot, E. & P. Kanagaratnam (2006). Changes in the velocity structure of the Greenland ice sheet. *Science*, 311, 986–990, doi:10.1126/science.1121381.

Rodriguez, E., & J.M. Martin (1992). Theory and design of interferometric synthetic aperture radars. In Radar and Signal Processing, IEE Proceedings F (Vol. 139, No. 2, pp. 147-159).

Scambos, T., Fricker, H. A., Liu, C. C., Bohlander, J., Fastook, J., Sargent, A., ... & Wu, A. M. (2009). Ice shelf disintegration by plate bending and hydro-fracture: Satellite observations and model results of the 2008 Wilkins ice shelf break-ups. *Earth and Planetary Science Letters*, 280(1), 51-60.

Schjøth, F., Andresen, C. S., Straneo, F., Murray, T., Scharrer, K., & Korablev, A. (2012). Campaign to map the bathymetry of a major Greenland fjord. *EOS*, Transactions American Geophysical Union, 93(14), 141-142.

Schoof, C. (2007). Ice sheet grounding line dynamics: steady states, stability, and hysteresis. *J. Geophys. Res*., 112, F03S28, doi:10.1029/2006JF000664.

Sergeant, A., Mangeney, A., Stutzmann, E., Montagner, J. P., Walter, F., Moretti, L., & Castelnau, O. (2016). Complex force history of a calving-generated glacial earthquake derived from broadband seismic inversion. *Geophysical Research Letters*. DOI: 10.1002/2015GL066785.

Shepherd, A., A. Hubbard, P. Nienow, M. King, M. McMillan, and I. Joughin (2006). Greenland ice sheet daily motion coupled with daily melting in late summer. *Geophysical Research Letters*, 36, L01501, doi: 10.1029/2008GL035758.

Strozzi, T., C. Werner, A. Wiesmann, & U. Wegmuller (2012), Topography mapping with a portable real-aperture radar interferometer. *Geoscience and Remote Sensing Letters*, IEEE, 9(2), 277-281.

Taylor Z.J., R. Gurka, GA and A. Liberzon (2010). Long-duration time-resolved PIV to study unsteady aerodynamics. *IEEE Transactions on Instrumentation and Measurement*, 59(12), 3262–3269.

Timoshenko, S. P., and J. N. Goodier (1970). Theory of Elasticity, 3rd ed., 567 pp., McGraw-Hill, New York.

Truffer, M., & Motyka, R. (2016). Where glaciers meet water: Subaqueous melt and its relevance to glaciers in various settings. *Reviews of Geophysics.*

Vaňková, I., & Holland, D. M. (2016). Calving Signature in Ocean Waves at Helheim Glacier and Sermilik Fjord, East Greenland. *Journal of Physical Oceanography.*

Van der Veen, C.J. (1998) Fracture mechanics approach to penetration of surface crevasses on glaciers. *Cold Regions Science and Technology*, 27, 31-47.

Van der Veen, C.J. (2002), Calving glaciers. *Progress in Physical Geography*, 26, 96–122.

Vaughan, D. G. & R. Arthern (2007). Why is it hard to predict the future of ice sheets? *Science*, 315, 1503-1504, doi:10.1126/science.1141111.

Vieli, A., & Nick, F. M. (2011). Understanding and modelling rapid dynamic changes of tidewater outlet glaciers: issues and implications. *Surveys in Geophysics*, 32(4-5), 437-458.

Voytenko, D., Dixon, T.H., Howat, I.M., Gourmelen, N., Lembke, C., Werner, C.L., De La Peña, S. and Oddsson, B., (2015a). Multi-year observations of Breiðamerkurjökull, a marine-terminating glacier in southeastern Iceland, using terrestrial radar interferometry. *Journal of Glaciology*, 61(225), 42-54.

Voytenko, D., Stern, A., Holland, D. M., Dixon, T. H., Christianson, K., & Walker, R. T. (2015b). Tidally driven ice speed variation at Helheim Glacier, Greenland, observed with terrestrial radar interferometry*. Journal of Glaciology*, 61(226), 301-308.

Walker, C.C., J.N., Bassis, H.A. Fricker, and R.J. Czerwinski (2015). Observations in the interannual and spatial variability in rift propagation in the Amery Ice Shelf, Antarctica 2002-2014, *J. Glaciol.,* 1(226), 243-252, doi:10.3189/2015JoG14J151.

Walter, J. I., J. E. Box, S. Tulaczyk, E. E. Brodsky, I. M. Howat, Y. Ahn, and A. Brown (2012), Oceanic mechanical forcing of a marine-terminating Greenland glacier, Ann. Glaciol., 53(60), 181-192(12), doi:10.3189/2012AoG60A083.

Weijer, W., Maltrud, M. E., Hecht, M. W., Dijkstra, H. A., & Kliphuis, M. A. (2012). Response of the Atlantic Ocean circulation to Greenland Ice Sheet melting in a strongly-eddying ocean model. *Geophysical Research Letters,* 39(9).

Werner, C., T. Strozzi, A. Wiesmann, & U. Wegmuller (2008) A real-aperture radar for ground-based differential interferometry. *Geoscience and Remote Sensing Symposium*. IGARSS 2008. IEEE International, IEEE, vol. 3, III–210.

Xie, S., T. Dixon, D. Voytenko, D.M. Holland, D. Holland, and T. Zheng, 2016: Precursor motion to iceberg calving at Jakobshavn Isbræ, Greenland, observed with terrestrial radar interferometry. Journal of Glaciology, http://dx.doi.org/10.1017/jog.2016.104.